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The UK solar energy resource and the impact of climate change

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ABSTRACT

Solar energy use in the UK is increasing dramatically, providing both heat energy and generation of electricity. This trend is expected to continue due to solar technologies becoming cheaper and more readily available along with low carbon government legislation such as the Renewable Heat Incentive (RHI) and Feed in Tariffs (FiTs) supporting solar energy deployment. However, the effects of climate change on the solar resource remain largely unstudied. Climate change affects cloud cover characteristics and consequently directly affects the performance of solar energy technologies.

This paper investigates the UK solar irradiation resource for both the present and future climates.

The present solar irradiation level was assessed through the conversion of 30 years of observed historical monthly average sunshine duration data. The method and results are validated by comparing the converted solar irradiation levels to actual solar irradiance measurements at weather stations with significant historical records of solar irradiance data.

The impact of climate change is investigated across different regions of the UK by using the UKCP09 probabilistic climate change projections.

We find that the current average UK annual solar resource is 101.2 Wm^{-2}, ranging from 128.4 Wm^{-2} in the south of England to 71.8 Wm^{-2} in the northwest of Scotland. It seems likely that climate change will increase the average resource in the south of the UK, while marginally decreasing it in the Northwest. The overall effect is a mean increase of the UK solar resource, however it will have greater seasonal variability and discrepancies between geographical regions will be reinforced.

1. Introduction

The UK has a target to meet 15% of its energy consumption from renewable sources by 2020 [1]. In order to achieve this, the generation capacity from renewable sources is increasing rapidly. Currently wind is the dominant renewable energy source in the UK, however the solar resource is huge and solar energy use in the UK is increasing (at the end of 2012 totalling 1.8 GW of PV capacity with 925 MW installed in 2012 [2]). Solar PV is commonly deployed in commercial and domestic buildings, and it offers the most appropriate source of distributed renewable energy generation in urban areas, due to the ease of incorporating solar PV into building materials. Small scale solar PV generation also qualifies for the FITs scheme, a government incentive to increase energy production from renewable energy. Solar PV converts global solar irradiance into electricity via the photo-generation of charge carriers in a semi-conducting material such as silicon.

It is ironic that much of the motivation to use renewable sources of energy generation comes from the desire to mitigate climate change, and climate change directly affects renewable energy resources. In the case of solar energy, cloud cover is the most important property of the climate to consider. Human activity causing an increase in atmospheric particles (aerosols) can in turn increase cloud cover by providing greater numbers of cloud condensation nuclei. Global solar irradiance levels depend on the cloud cover characteristics, and therefore will change due to climate change.

When considering solar energy as a sustainable energy solution it is therefore important not only to quantify the present solar resource but to try and anticipate how the solar resource will change along with any climate change in the future.

The UK Climate projections UKCP09 [8] have been designed to show how the future climate may differ (from the current climate) due to the past and current levels of greenhouse gas emissions. The projections offer 3 different future climate scenarios corresponding to Low, Medium and High greenhouse gas emissions, with the output for each scenario being a normal distribution of the change in the desired variable. In this manner probability levels can be

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associated with a certain change (here we use 10%, 50% and 90% probability levels). The climate projection variables include the change in downward surface shortwave radiation flux (Wm^{-2}).

There has been some previous work to try and gauge the effects of climate change on solar energy. Ref. [3] examines global changes in PV and concentrated solar power outputs, using two climate change models (HadGEM1 and HadCM3) and a single emissions scenario. They conclude that CSP is more sensitive to climate change than PV and overall solar power from 2010 to 2080 will increase a few percent in Europe and China, stay similar in Algeria and Australia and decrease by a few percent in USA and Saudi Arabia. Ref. [6] investigates the uncertainty in long term solar resource datasets is the U.S., highlighting the seasonal components in the solar resource, aiming to provide a better understanding of the solar resource for particular applications. Ref. [9] uses a regional climate change model and suggests that seasonal-mean daily global irradiance in the US may decrease by up to 20% by the end of the 2040's. Recent work by Ref. [24] reviews the adaptability to climate change of California's electricity sector as a whole. Similar work has been done relating to wind energy, e.g. [12] reviews the mechanisms by which wind energy can interact with climate change, focussing on Northern Europe, and conclude that in the near term (up to 2050's) climate change will have little effect compared to natural variability. Ref. [13] characterises the UK wind resource by examining recent trends in wind speed measurements, but does not discuss climate change. There is relatively little available literature relating to the UK solar resource and the impact of climate change on this resource. In this work we characterise the UK solar resource providing a detailed assessment. Then combining this with the UKCP09 outputs, we examine the effect of climate change to give estimates of the future UK solar resource, in order to inform PV manufacturers, developers and policy makers alike.

2. Method

2.1. Baseline resource assessment

A UK solar resource assessment of the present climate would ideally be performed using solar irradiance historical measurements. However, there are very few weather stations that have sufficiently long historical solar irradiance observation data to be of use for evaluation over a 30 year time period.

Solar irradiance is measured using Pyranometers or Pyrheliometers. Pyranometers measure horizontal solar irradiance (global solar irradiance) while pyrheliometers measure direct normal solar irradiance. The former are more commonly deployed in the UK, and are more relevant to solar PV as it utilises both diffuse and direct solar irradiance. Solar irradiance can also be indirectly calculated from sunshine duration observation measurements. Sunshine duration is more commonly measured at weather stations; the measurement device is a Campbell Stokes Sunshine Recorder which has been in use since the late nineteenth century. Hence there is a long historical time series of available data at many UK locations.

The Met Office has developed UK gridded observed sunshine duration data sets which are based on observations from an average of 290 weather station locations across the UK [10,11]. This data has been used to develop annual monthly average 5 km × 5 km gridded data sets of daily sunshine duration over the UK. The gridded data sets cover in excess of 30 years and were used as the main source of observed sunshine duration. Here, the sunshine duration data was converted to solar radiation using a method described by Ref. [14] and then averaged over a 30 year baseline period (1961–1990). Verification of the conversion method was achieved by comparing the converted data with actual observed solar irradiation data from several locations across the UK (weather stations which have pyranometers).

The baseline resource is essentially an estimation of the UK solar resource for the current climate. It is averaged over a 30 year period to remove inter-annual variability. The baseline period of 1961–1990 has been chosen to match the baseline period used by UKCP09.

Satellite inferred solar irradiance data for Europe is also available (e.g. Ref. [19]) and provides a very useful resource for the analysis of large regions, especially where ground based measurements are sparse. However for this study there were a number of reasons why it was not used. In order to best project outputs from the UKCP09 model on to a baseline solar resource, the baseline was generated using observations from the same time period as used by the UKCP09 model (1961–1990) for which satellite data was unavailable. Satellite inferred data is also less accurate than ground based measurements when met stations are close together (especially so during winter months due to difficulty in the satellite models of distinguishing frost, low-cloud, fog and snow etc) and it also has a lower spatial resolution than the gridded met office data. Significant discussion about how well satellite inferred data fits with observed ground measurements can be found in Ref. [23].

An accurate UK solar energy baseline resource map was created by converting a 30 year time series of monthly average daily sunshine duration observation data sets to solar irradiance.

2.2. Observation data

The ‘UKCP09: Gridded observation data sets’ were created primarily to assist with research into climate change and adaptation. They include sunshine duration data for the UK with a resolution of 5 km × 5 km for the 1961–1990 baseline time period. The raw data has been subjected to regression and interpolation to generate regular values from the irregular station network, and the dataset output also accounts for other attributes such as location, altitude, terrain, coastal influence, and land use [10,11].

The UK 5 km gridded sunshine duration data was converted to global irradiance using a method introduced by Ref. [14]. This is based on the widely used Angstrom–Prescott equation which describes a relationship between the relative sunshine duration and solar irradiance on the surface of the earth. (See Ref. [7] for a historical appraisal of the evolution of the Angstrom–Prescott equation). There have been several studies that have tested Suehrcke's sunshine duration to radiation relationship with favourable results. Ref. [4] tests the Suehrcke relationship, concluding that it is of ‘prime interest’ due to ‘its simplicity and the elegance of its derivation’ and that it is adequate but no more accurate than the Angstrom-Prescott method at estimating monthly average values. Ref. [18] found Suehrcke's relationship to give slightly better accuracy than the Angstrom–Prescott method.

The advantage that the Suehrcke method has over the Angstrom–Prescott method is that it does not rely on two empirically derived, location specific constants. Instead, the Suehrcke method requires only an estimate of the monthly average daily clear sky clearness index. Ref. [14]. states the value as being ‘typically between 0.65 and 0.75’. The next section briefly outlines the Suehrcke conversion method.

2.3. Suehrcke conversion method

Monthly average daily sunshine duration data was converted to solar irradiance using Suehrcke's derived equation relating the sunshine fraction to monthly average of daily horizontal extraterrestrial solar radiation [14]. The process of relating sunshine hours to solar irradiance on a horizontal plane requires the calculation of several other parameters including: length of the day, sunrise/sunset hour angle, declination of the sun and extra-terrestrial solar radiation. These can be calculated using the empirical equations (1)–(8); the method is also described in many standard solar resource textbooks [20], [5], [15]. All calculations assume that cloud cover has uniform characteristics throughout the day and solar irradiance is isotropic.

Suehrcke's equation states:

$$f_{\text{clear}} = \left(\frac{\overline{K}}{\overline{K}_{\text{clear}}}\right)^2 \tag{1}$$

where f_{clear} is the fraction of time which no significant clouds block the sun, $\overline{K}$ is the monthly average daily clearness index and $\overline{K}_{\text{clear}}$ is the monthly average clear sky clearness index. $\overline{K}$ and $\overline{K}_{\text{clear}}$ are dimensionless.

The variable f_{clear} for a specific month and location is equivalent to the sunshine fraction (S). The sunshine fraction can be calculated by dividing the average monthly sunshine duration data by the average monthly day length. Day length can be calculated using:

$$N = \frac{2}{15}\cos^{-1}(-\tan\phi\tan\delta) \tag{2}$$

where N is day length in hours, ϕ is the latitude in degrees and δ is the declination of the sun in degrees. The declination of the Sun (δ) is given by:

$$\delta = 23.45\sin\left[360\frac{284+n}{365}\right] \tag{3}$$

where n is the day of the year starting on 1st January.

The monthly average clear sky clearness index $\overline{K}_{\text{clear}}$ is calculated by

$$\overline{K}_{\text{clear}} = \frac{\overline{H}_{\text{clear}}}{\overline{H}_{\text{o}}} \tag{4}$$

where $\overline{H}_{\text{clear}}$ is the monthly average of daily horizontal surface clear sky irradiation (J m^{-2}) and $\overline{H}_{\text{o}}$ is the monthly average of daily horizontal extra-terrestrial solar irradiation (J m^{-2}). The monthly average clear sky clearness index $\overline{K}_{\text{clear}}$ is the component in Suehrcke's equation that removes the requirement of the two empirical constants in the Angstrom–Prescott method.

The monthly average daily clearness index $\overline{K}$ is defined as:

$$\overline{K} = \frac{\overline{H}_{\text{h}}}{\overline{H}_{\text{o}}} \tag{5}$$

where $\overline{H}_{\text{h}}$ is the monthly average of daily horizontal surface irradiation.

The daily horizontal extra-terrestrial solar irradiation variableH_o is described by

$$H_{\text{o}} = \frac{3600*24}{\pi} I_0 * \frac{\pi h_{\text{ss}}}{180}(\sin\phi\sin\delta + \cos\phi\cos\delta\sin h_{\text{ss}}) \tag{6}$$

where h_{ss} is the sunrise/sunset hour angle on a horizontal surface and I_{o} is the extra-terrestrial solar radiation at normal incidence. h_{ss} can be calculated by

$$h_{\text{ss}} = \cos^{-1}(-\tan\phi\tan\delta) \tag{7}$$

while I_{o} can be calculated by

Table 1
Locations of the eighteen Met stations measuring both sunshine duration and global solar irradiance shown in Fig. 1.

Station	Location (latitude, longitude)	Station	Location (latitude, longitude)
SRC1395	50.218, −5.329	SRC535	53.827, −1.147
SRC846	50.742, −1.574	SRC1105	54.014, −2.774
SRC744	51.287, 0.451	SRC1450	54.664, −6.224
SRC838	51.39, −0.784	SRC332	54.903, −1.393
SRC825	51.603, −1.111	SRC1023	55.311, −3.206
SRC471	51.806, −0.358	SRC181	56.459, −3.072
SRC1198	52.139, −4.571	SRC113	57.206, −3.827
SRC443	52.686, 1.693	SRC54	58.214, −6.325
SRC554	52.836, −1.250	SRC09	60.14, −1.183

$$I_{\text{o}} = I_{\text{sc}}\left(1 + 0.033\cos\frac{360}{365}n\right) \tag{8}$$

where I_{sc} is the solar constant and is equal to 1367 Wm^{-2}.

Unfortunately $\overline{H}_{\text{clear}}$ is a parameter that is not readily available from observed data. Therefore, an alternative method of determining $\overline{K}_{\text{clear}}$ has been used: $\overline{K}_{\text{clear}}$ values were identified by calibrating the value of $\overline{K}_{\text{clear}}$ in the Suehrcke conversion equation against actual observed solar irradiance data. This process essentially makes it empirical (see Table 1).

3. Resource analysis

3.1. Estimation of $\overline{K}_{clear}$ values

Eighteen UK meteorological stations were identified that observed both sunshine duration and solar irradiance, and also had sufficiently long historical data for both parameters. The eighteen locations are shown in Fig. 1. A daily time series of 5 years (1995–1999) of both sunshine duration and daily irradiation was

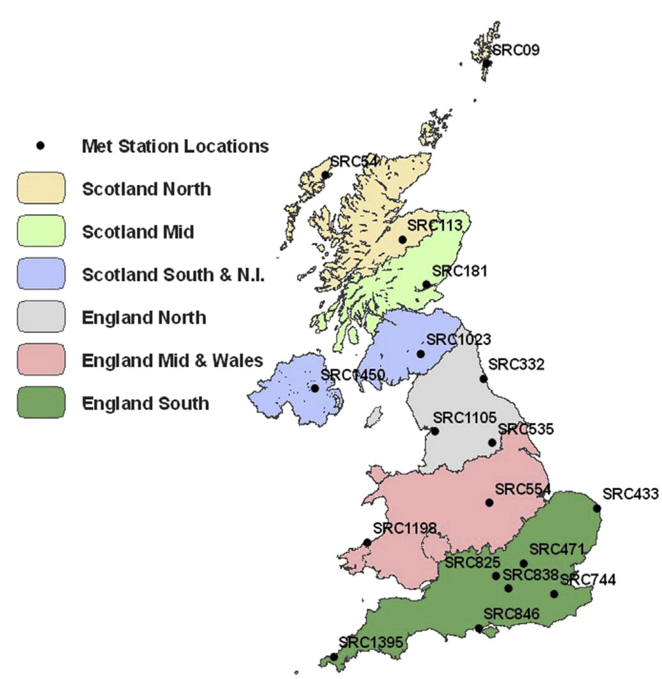

Fig. 1. Locations of met stations measuring both sunshine duration and global irradiance. The solar resource regions considered in Section 5 are also shown.

Table 2
Average $\overline{K}_{clear}$ values for the UK for 5 years (1995–1999) for the eighteen stations shown in Fig. 1.

Month	Average $\overline{K}_{clear}$	RMSE
January	0.579	0.0259
February	0.63	0.0275
March	0.668	0.0254
April	0.682	0.0243
May	0.701	0.0169
June	0.707	0.0305
July	0.71	0.0191
August	0.679	0.0165
September	0.667	0.0160
October	0.641	0.0249
November	0.628	0.0332
December	0.616	0.0738

downloaded for all eighteen met stations [21] and used for the analysis of the $\overline{K}_{clear}$ values. The average monthly converted sunshine duration values for all stations were adjusted to match the observed monthly global solar irradiation by optimising the value of $\overline{K}_{clear}$ for each month. The UK average values for $\overline{K}_{clear}$ and the Root Mean Square Error (RMSE) are shown in Table 2. The $\overline{K}_{clear}$ variability between stations and the average monthly values are shown in Fig. 2.

The RMSE can be calculated by

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2}{n}} \tag{9}$$

where X_i is the met station $\overline{K}_{clear}$ value, $\overline{X}$ is the average of the met station $\overline{K}_{clear}$ values, and i is the met station number.

Within the bounds of the UK there does not appear to be any correlation between the $\overline{K}_{clear}$ value and latitude or longitude of location. For instance, three stations that have marginally higher values (src113, src1198, src1395) are located in North Scotland, Wales, and South West England respectively.

Using the values for $\overline{K}_{clear}$ as shown in Table 2 and knowing f_{clear}, the $\overline{K}$ values can now be calculated from Equation (1). They are directly related to the monthly average of daily horizontal extra-terrestrial solar irradiation as shown in Equation (5). Substituting in values for both $\overline{K}$ and $\overline{H}_o$ ($\overline{H}_o$ is calculated using Equation (6)) into Equation (5), the monthly average of daily horizontal surface irradiation$\overline{H}_h$, the parameter that is ultimately being sought, can be calculated.

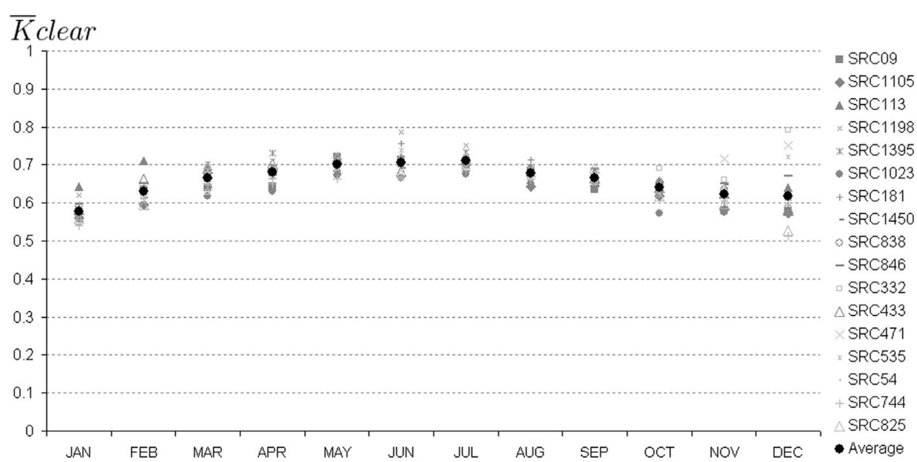

Fig. 2. Illustrating the Monthly variability of $\overline{K}_{clear}$ for the different met stations used in the $\overline{K}_{clear}$ validation.

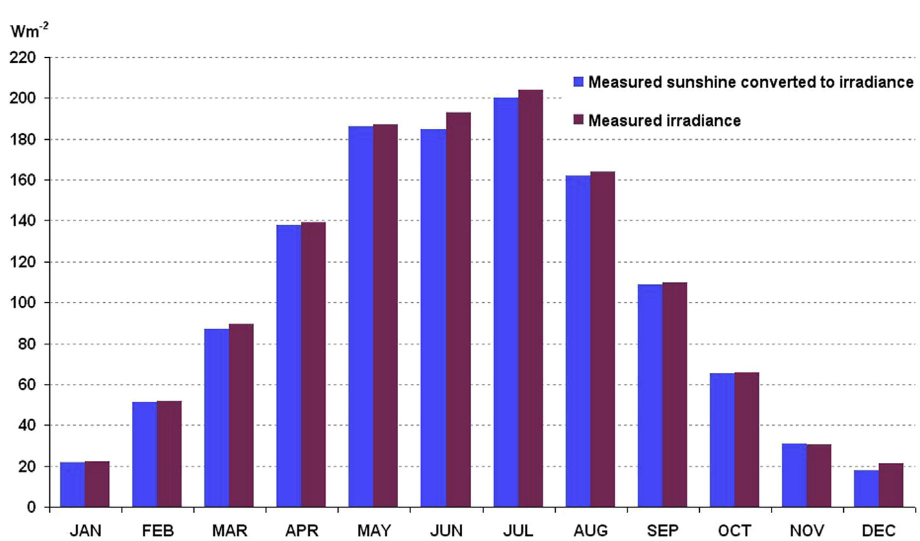

Fig. 3. Comparison of measured sunshine hour duration converted to irradiance and actual measured irradiance for station SRC535.

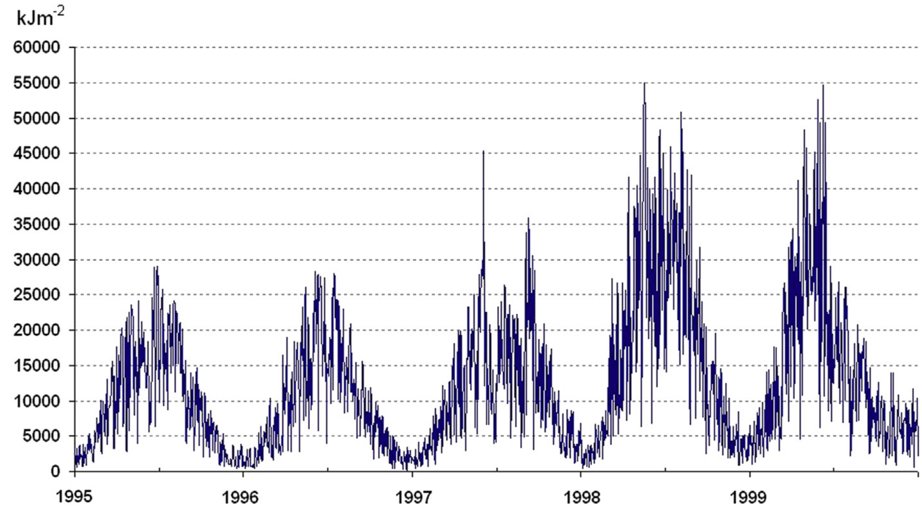

Fig. 4. Erroneous solar radiation readings at station SRC554. The error is clearly illustrated in the years 1997–1999.

3.2. Validation of the Suehrcke conversion method

Fig. 3 shows data for the met station SRC535 located in North Yorkshire. The close relationship of the converted measured sunshine hours with average measured solar irradiance is typical for most of the locations shown in Fig. 1. At this stage in the process one of the weather stations (SRC554 in Nottinghamshire) was identified as having anomalous data. The higher values in the measured solar radiation for met station SRC554 were investigated and found to be caused by erroneous spikes in the pyranometer readings throughout years three, four and five (see Fig. 4), possibly from a defective sensor or positioning issues. All pyranometer data from the other locations had normal characteristics and were free from any similar spikes. Hence readings from this weather station were discounted. For all the other weather stations, the averaged monthly sunshine hours converted to irradiance and the measured average monthly irradiance differ by an average of 5 Wm^{-2}.

3.3. Conversion of UK 5 km gridded sunshine duration to solar radiation

The 5 km gridded data sets of monthly average daily sunshine duration [21] were obtained for the years from 1961 to 2005. Irregular or missing data-points were replaced by interpolation from adjacent cells. Fig. 5 illustrates the 30 year (1961–1990) averaged sunshine durations showing Annual, June and December values.

Sunshine duration data from each 5 km cell of each month from 1961 to 1990 was converted into solar irradiance using the Suehrcke method. An annual baseline solar irradiance resource dataset was also created by averaging the UK monthly values of $\overline{K}_{\text{clear}}$. Fig. 6 shows the average daily annual sunshine hour duration over the baseline period and the converted baseline annual UK solar radiation resource map.

3.4. Validation of baseline resource

Again the validation of the gridded baseline solar radiation model was completed by comparing the derived and actual solar resource data from the eighteen weather stations [21] shown in Fig. 1, with the derived solar irradiance data calculated from the gridded sunshine duration data sets at each station location over the same time period (1995–1999).

Fig. 7 shows the month of June and Fig. 8 shows the month of January for all locations. The close relationship is typical for all the other months. It is unclear why the converted gridded and station sunshine duration values are slightly different at some locations, as the gridded data at each station location should have been generated

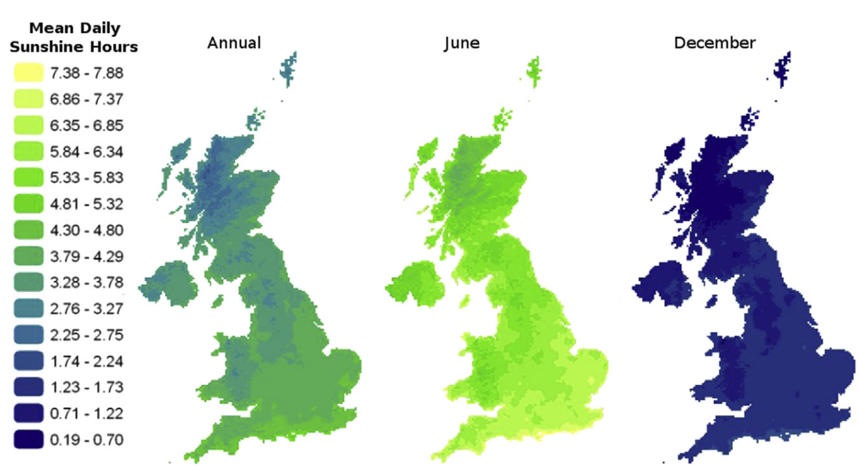

Fig. 5. Monthly average daily sunshine duration hours – baseline resource (1961–1990).

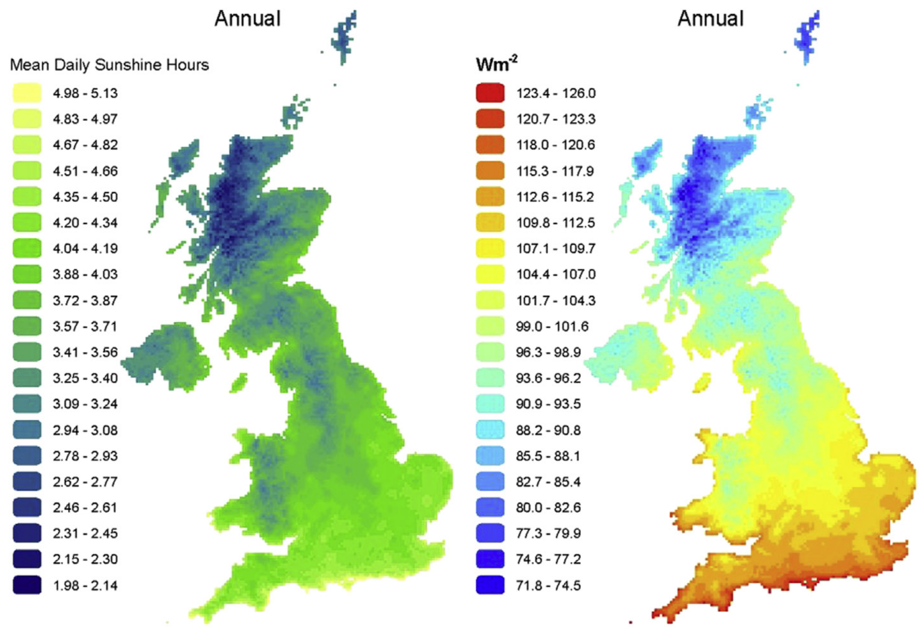

Fig. 6. Average daily annual sunshine hours and converted solar irradiance over the baseline time period.

from the station sunshine duration measurements. Differences may have been introduced due to the interpolation process used to create the gridded data, or it is possible that not all the sunshine duration data may have been used to create the gridded data.

Table 3 shows error values between actual measured solar irradiance and derived solar irradiance values from sunshine hours at the station and sunshine values from the gridded data for the same years and locations. SRC554 was not included in the overall average figures.

The UK baseline solar resource estimated using the gridded sunshine duration data (as shown in Fig. 6) at selected UK locations was also compared with values from the Photovoltaic Geographic Information System (PV-GIS) [16], which is a GIS integrated European solar radiation database that derives the different solar irradiance components at a chosen location. The primary PV-GIS model input parameters were solar irradiance observations from 566 met stations (spread over Europe and North Africa, with 54 UK based stations) over the period 1981–1990 [16]. The PV-GIS values are compared with the UK baseline resource estimated using sunshine duration data for a spread of UK locations as shown in Table 4.

Table 4 shows that PV-GIS predicts slightly higher values, especially in higher latitude locations. The chosen locations have been used to illustrate a range of latitudes across the UK.

The PV-GIS values have an average offset of 4.3 Wm^{-2} (+4.4%) with a standard deviation of 2.55 Wm^{-2} when compared with the figures estimated in this study. PV-GIS also state that their figures have an estimated annual average cross-validation RMSE value of 4.5% [17]. There is negligible offset between the actual monthly observed radiation values and those converted from the sunshine duration values in this report. The discrepancy between PV-GIS and the converted sunshine duration data used in this analysis is likely to come from the different baseline periods (PV-GIS used 1981–1990 whereas here 1961–1990 is used) and the different numbers of UK met stations used for the interpolation.

The UK solar estimates here are a better representation of the current UK climate, as they have been generated using data that has

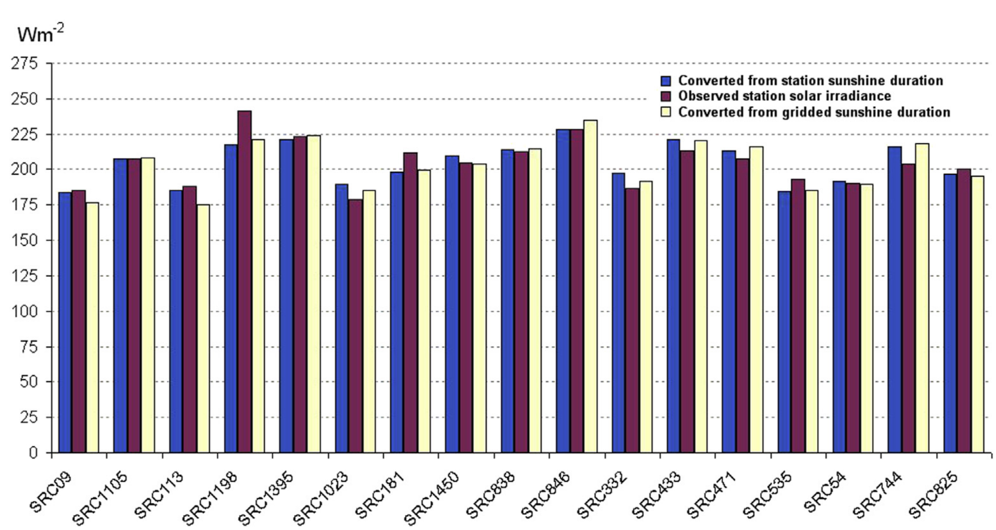

Fig. 7. Comparison of gridded sunshine duration converted to irradiance with measured irradiance at all 18 locations for the month of June.

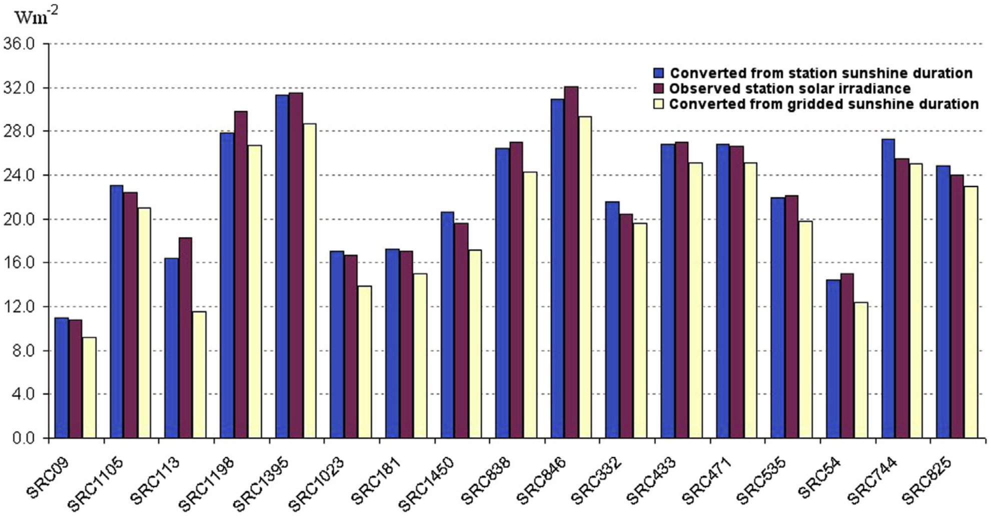

Fig. 8. Comparison of gridded sunshine duration converted to irradiance with measured irradiance at all 18 locations for the month of January.

been averaged over a longer time period (30 years as opposed to 10 years) and use many more UK based met stations (approx. 290 as opposed to 54).

3.5. Uncertainties

It should also be noted that the data and method contain a number of uncertainties. The accuracy of the sunshine and radiation recordings are generally within a few percent but poor maintenance or obstructions shading the sun from the instruments, such as buildings or trees can introduce errors. Systematic errors in the Campbell Stokes meters may be up to 20% at times; if there are two short bursts of bright sunshine in a close period the burns on the card can be wrongly read as one continual longer burst [22]. The resolution of the gridded sunshine data does not capture all characteristics of the terrain and shaded locations and will lead to larger errors at some locations.

Table 3
Error comparisons from observed solar radiation to observed converted sunshine hours from the same met station and to converted gridded sunshine hours. All values have been rounded to the nearest hundredth Wm^{-2}.

Station ID	Station			Grid		
	R^2	RMSE (Wm^{-2})	Mean error (Wm^{-2})	R^2	RMSE (Wm^{-2})	Mean error (Wm^{-2})
SRC09	1.00	3.02	0.91	1.00	5.27	−4.05
SRC54	1.00	1.60	−0.36	1.00	5.43	−4.82
SRC113	1.00	2.82	−1.77	1.00	11.08	−10.45
SRC181	1.00	4.90	−1.79	1.00	5.52	−4.64
SRC332	1.00	4.51	1.22	1.00	3.99	−1.44
SRC433	1.00	3.36	−0.87	1.00	4.66	−2.36
SRC471	1.00	3.46	0.69	1.00	5.43	0.34
SRC535	1.00	2.94	−1.93	1.00	4.55	−3.97
SRC554	0.98	38.32	−33.69	0.97	41.07	−36.59
SRC744	1.00	6.00	4.70	1.00	7.00	3.85
SRC825	1.00	3.24	−1.08	1.00	4.58	−3.41
SRC838	1.00	2.60	1.45	1.00	3.81	−0.53
SRC846	1.00	2.47	−1.84	1.00	4.12	−0.99
SRC1023	1.00	6.26	5.20	1.00	3.17	−0.77
SRC1105	1.00	3.25	1.99	1.00	3.21	−0.50
SRC1198	1.00	5.19	−3.96	1.00	5.19	−4.66
SRC1395	1.00	4.52	−2.99	1.00	5.67	−4.43
SRC1450	1.00	2.99	1.91	1.00	3.22	−2.92
Overall Average	**1.00**	**3.71**	**0.09**	**1.00**	**5.05**	**−2.69**

Table 4
Comparing average annual horizontal surface irradiance with PV-GIS.

Location	Latitude, longitude	Horizontal solar irradiance (Wm^{-2})		
		Present analysis	PV-GIS (2011)	Difference
Lerwick	60.157, −1.144	82.2	90.0	−7.8
Thurso	58.595, −3.523	88.1	93.8	−5.7
Ullapool	57.896, −5.161	89.7	96.3	−6.6
Edinburgh	55.958, −3.189	98.0	100.4	−2.4
Carlisle	54.899, −2.934	102.0	103.3	−1.3
Birmingham	52.500, −1.892	104.9	109.6	−4.7
Southampton	50.907, −1.414	117.1	118.8	−1.7

4. Climate change impact

4.1. UKCP09 probabilistic projections

The UKCP09 probabilistic climate change projections [8] were used to explore the climate change impact on the UK's solar resource. A probabilistic projection assigns probability levels to a climate change output. The UKCP09 projections provide change values for a parameter in the future climate, expressed as a difference from the baseline climate. They give a measure of the likelihood of a certain change occurring. In this article we refer to the 10%, 50% and 90% levels of the Cumulative Distribution Function (CDF) of the projection outputs. The UKCP09 10% probability level has a 90% likelihood of being exceeded, the 50% probability level is equally likely to be exceeded as not, and the 90% probability level has only a 10% likelihood of being exceeded. The variable 'total downward surface shortwave flux' is one of sixteen UKCP09 probabilistic output variables over land and is the measure of horizontal solar radiation.

Two thirty year future time periods were explored: 2050s (2040–2069) and 2080s (2070–2099). Low, medium and high emissions scenarios and probabilistic data at 50%, 10%, and 90% probability were extracted from the UKCP09 projections. The settings for extraction were as follows:

Climate change type:	Future climate change only
Output variable:	Change in downward surface shortwave flux (Wm^{-2})
Emissions scenario:	2040–69 (2050s), 2070–99 (2080s)
Temporal average:	Monthly
Probability levels:	50% (10%, 90%)

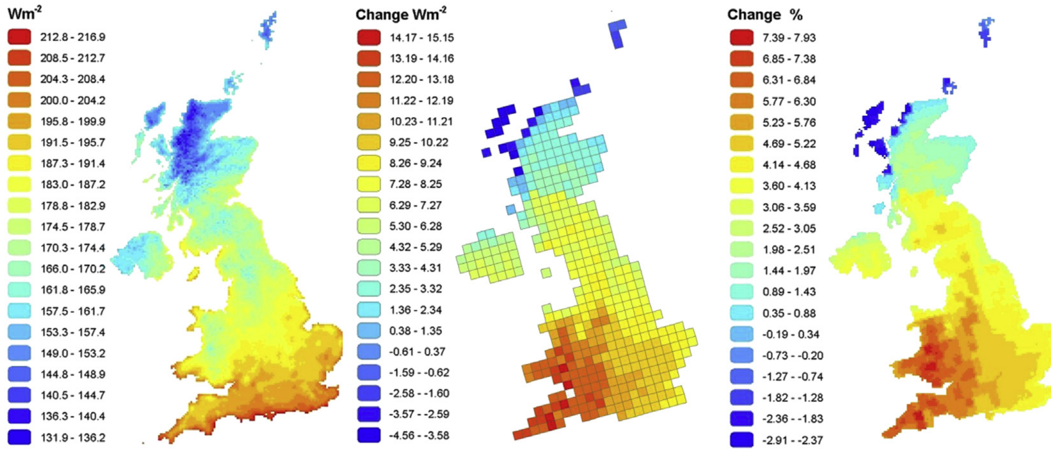

Fig. 9. Summer solar resource: baseline (left); (middle) 2050s change in Wm^{-2}; and (right) percentage change from baseline.

UKCIP09 'Change in total downward surface shortwave flux (Wm^{-2}) projection data was downloaded via the UKCP09 user interface for the low, medium and high emissions.

The projected average percentage change of horizontal surface solar irradiance can be calculated for the 2050s and 2080s by projecting the UKCP09 climate change values onto the baseline solar irradiance model. Fig. 9 shows the baseline resource for summer months (left); the UKCP09 2050s medium scenario relative change in Wm^{-2} from baseline with 50% probability (middle); and the resulting percentage change from baseline (right). It indicates significant solar irradiance increases in the south-west, with the increases becoming less significant further north with much of Scotland showing little change from baseline except in the far north and westerly regions of the Highlands of Scotland, where there are slight decreases in solar irradiance.

Fig. 10 shows the 10%, 50% and 90% probabilities for 2050s summer months in the medium emissions scenario. The 50% probability distribution shows the central estimate, the 10% is very likely to be exceeded and the 90% is very unlikely to be exceeded. The 50% figure is the same data as shown in Fig. 9 (right) but is shown on a wider scale to incorporate the 10% and 90% distributions and, therefore has less resolution. They show increases in the solar resource in spring, summer and autumn, especially towards more south westerly locations, and reductions in winter months UK wide.

5. Results: solar resource change by region

Six UK solar regions were created to help understand climate change impacts across the UK. The regions were created by merging together adjacent UKCP09 administrative regions with similar solar resource characteristics. The solar resource and climate projections of each of region were investigated. The UK regions are shown in Fig. 1.

Fig. 11 shows the monthly average baseline solar resource for all regions.

Table 5 and the charts in Fig. 12 show the regional specific impact of climate change over the UK. The table shows the change from the baseline resource in Wm^{-2} and the charts in Fig. 12 show average regional percentage change from the baseline value for the 2050s, medium scenario with 50% probability level. The intra annual variability of the resource change is apparent. The figure clearly shows a reduction of the solar resource over winter months in all regions with it being most apparent in northerly regions. In

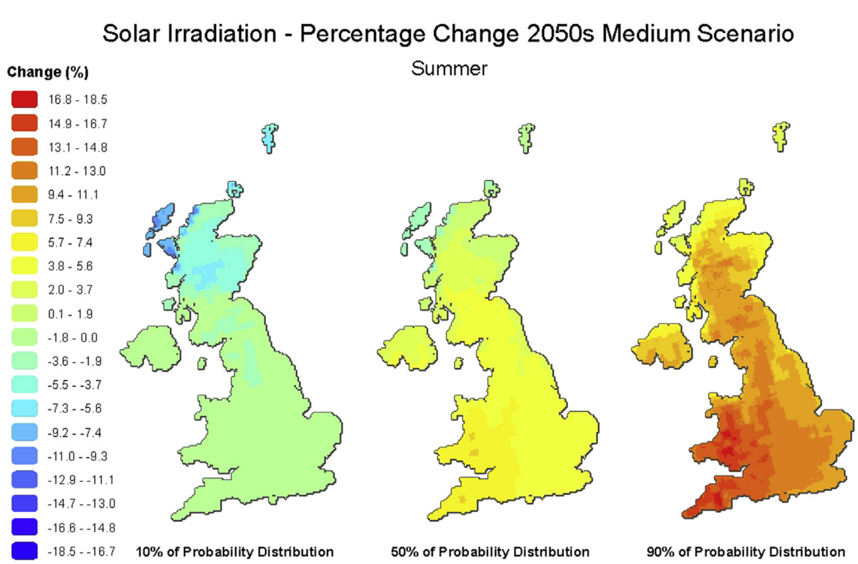

Fig. 10. Summer solar percentage change from baseline for 2050s medium scenario 50% (10%, 90%) probabilities.

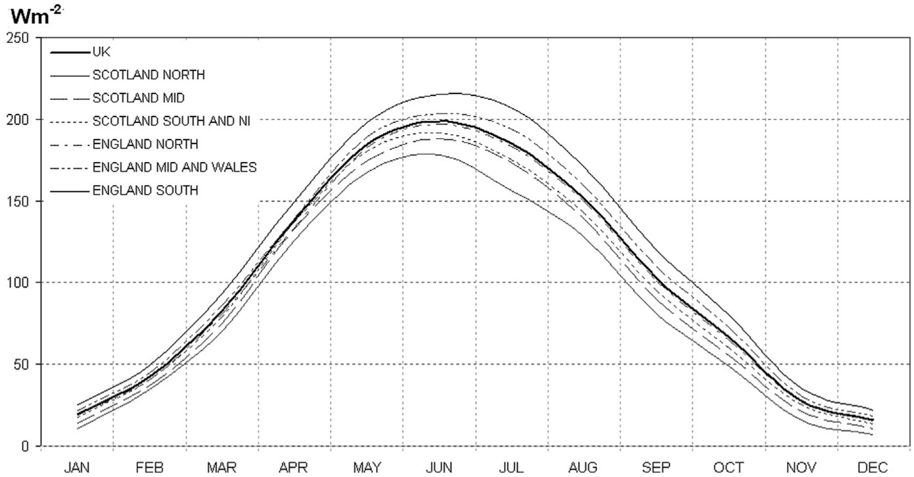

Fig. 11. UK solar regions baseline solar resource.

summer months nearly all areas show an increase in solar resource especially in southerly and south westerly regions. Summer months in north Scotland show a relatively flat response, just slightly above the zero mark for much of the period between spring and autumn.

By the 2050s, under a 'medium emissions' scenario, summer months show solar irradiance increases of up to 7.9% (within a range of −0.2% to 18.1%) in the south west. These reduce further north with decreases of up to −2.9% (within a range of −10.8% to 1.8%) in the north of Scotland. Winter months show a reduction throughout the UK with extremes of −7.6% (within a range of −25.2% to 10.1%) in mid-west Scotland. This suggests that most southern parts of the UK will get sunnier and benefit from increased solar energy resource in summer, while the relatively poor resources in the north will decrease slightly. All regions in winter will have increased cloud cover and a slightly reduced solar energy resource.

It is interesting to note that the low emissions scenario frequently shows more change than the medium scenario in the monthly 2050's projections, illustrating the complexity of the relationship between locality, emissions scenario and climate change impact. However, by the 2080's the low emissions scenario nearly always shows the least change; after the 2050's the emissions scenarios diverge more rapidly.

6. Conclusion

The current solar energy resource in the UK offers a huge untapped potential, especially in the south of England and Wales where the average daily solar irradiance is often in excess of 130 Wm^{-2}. It seems likely that in the places where the current resource is largest (in the south and south west), the resource will on average see a sizeable increase due to climate change. However, in those places where it is currently weaker, the resource will suffer a slight decrease. Assuming a high emissions scenario, the UK will see an overall annual increase of 3.6% by the 2050s (within a range of −0.9% to 8.5%) increasing to 4.4% (within a range of −1.9% to 11.2%) by the 2080s. This is positive news for the viability of solar technologies, particularly in southern regions and would correlate well with increased demand from the use of air cooling systems

Table 5
Annual regional solar radiation baseline resource, 2050's and 2080s change in Wm^{-2} for 10%, 50% and 90% probability levels.

Region	Current baseline average resource (Wm^{-2})	Emissions scenario	Change at probability level (Wm^{-2}), 2050's			Change at probability level (Wm^{-2}), 2080's		
			10%	50%	90%	10%	50%	90%
UK	101.2	Low	−0.9	3.5	8.0	−1.0	3.7	8.7
		Medium	−1.2	3.0	7.4	−1.1	3.9	9.2
		High	−0.9	3.6	8.5	−1.9	4.4	11.2
Scotland North	85.3	Low	−2.8	0.4	3.6	−3.6	0.0	3.5
		Medium	−3.5	−0.2	3.1	−4.4	−0.3	3.6
		High	−3.5	0.0	3.4	−5.8	−1.0	3.6
Scotland Mid	92.6	Low	−2.2	1.5	5.1	−2.9	1.2	5.4
		Medium	−2.9	0.8	4.6	−3.5	1.1	5.8
		High	−2.7	1.3	5.3	−4.8	0.9	6.6
Scotland South and Northern Ireland	96.5	Low	−0.9	2.6	6.1	−1.1	2.7	6.7
		Medium	−1.2	2.1	5.5	−1.2	2.7	6.9
		High	−1.1	2.7	6.6	−2.0	3.1	8.5
England North	99.5	Low	−0.5	3.6	8.0	−0.7	3.9	8.7
		Medium	−0.9	3.0	7.2	−0.7	4.0	9.1
		High	−0.6	3.8	8.5	−1.5	4.6	11.3
England Mid and Wales	105.7	Low	−0.1	4.7	9.7	0.0	5.1	10.8
		Medium	−0.1	4.4	9.2	0.4	5.6	11.5
		High	0.2	5.1	10.5	−0.2	6.5	14.2
England South	113.7	Low	0.1	5.6	11.5	0.3	6.2	12.8
		Medium	0.0	5.3	11.0	0.7	6.8	13.8
		High	0.5	6.2	12.4	0.2	8.0	17.0

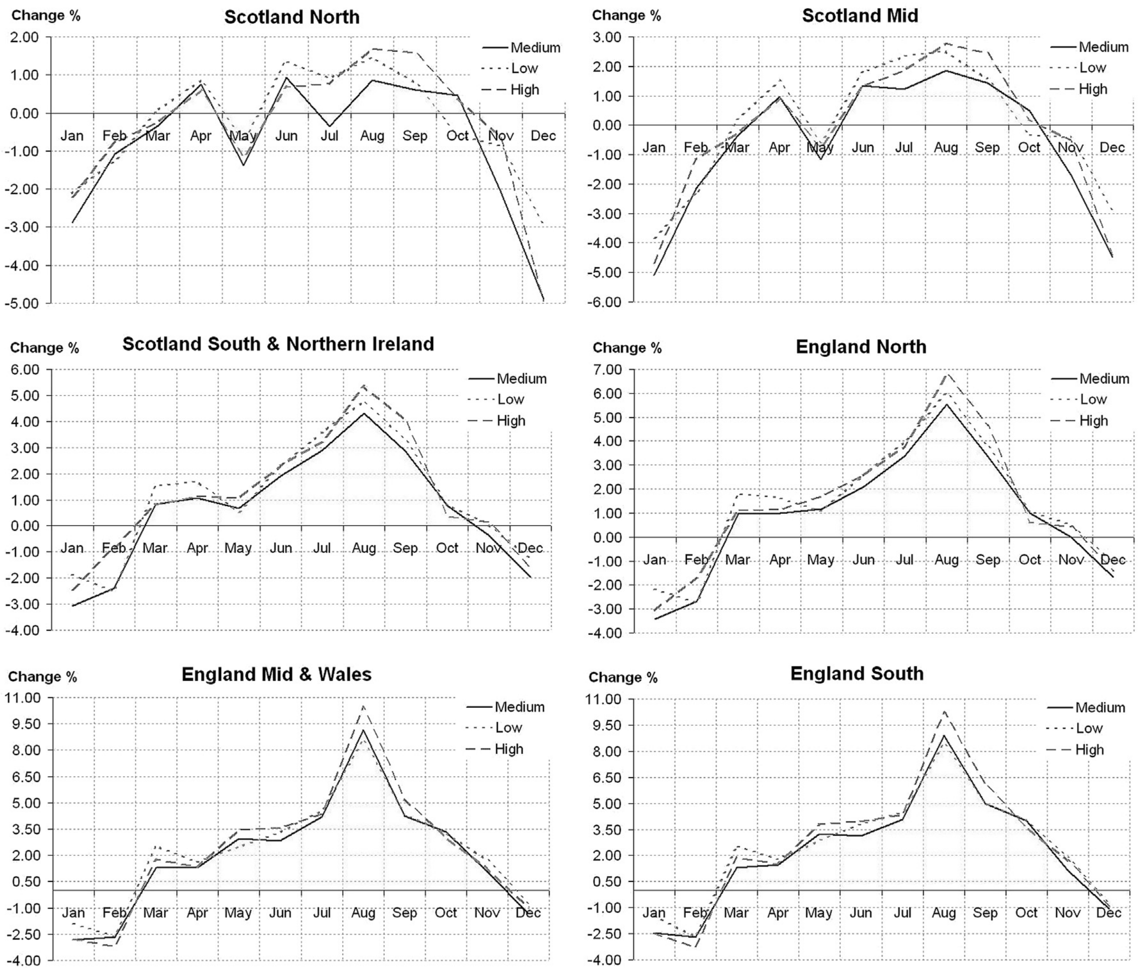

Fig. 12. Regional average percentage change from baseline for the 2050s.

due to increased ambient temperatures. In terms of solar PV we expect the change in the UK solar resource to be broadly reflected in the change in solar PV outputs. However, we anticipate that the existing regional differences in the solar resource will be further reinforced. While intra-monthly variation has not been examined in great detail, it is evident that climate change will result in higher intra-annual variability of the UK solar resource, especially in more southerly UK locations.

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